

# Binary black hole mergers in magnetized disks: simulations in full general relativity

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We present results from the first fully general relativistic, magnetohydrodynamic (GRMHD) simulations of an equal-mass black hole binary (BHBH) in a magnetized, circumbinary accretion disk. We simulate both the pre and post-decoupling phases of a BHBH-disk system and both “cooling” and “no-cooling” gas flows. Prior to decoupling, the competition between the binary tidal torques and the effective viscous torques due to MHD turbulence depletes the disk interior to the binary orbit. However, it also induces a two-stream accretion flow and mildly relativistic polar outflows from the BHs. Following decoupling, the accretion rate is reduced, while the EM luminosities peak near merger due to shock heating. This investigation, though preliminary, previews more detailed GRMHD simulations we plan to perform in anticipation of future, simultaneous detections of gravitational and electromagnetic radiation from a merging BHBH-disk system.

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When galaxies merge, massive black hole binaries (BHBHs) are likely to form in gas rich environments [1]. These systems may provide a unique opportunity for a simultaneous detection of electromagnetic (EM) and gravitational waves (GWs) from the same cosmic event.

If BHBHs are embedded in a gas with negligible angular momentum, the accretion flow will resemble the Bondi or Bondi-Hoyle-Lyttleton accretion solutions [2–4]. When the gas has intrinsic angular momentum, it will form a circumbinary disk that accretes via angular momentum transport induced by an effective viscosity. The BHBH-disk problem has been studied extensively in Newtonian gravitation, both analytically [5–9], where the emphasis has been on low mass-ratio binaries, and numerically [5, 10, 11] where equal-mass systems have been the focus. The goal is to compute observable EM “precursor” and “aftermath” radiation that will accompany the GW signal. While the vacuum BHBH [12] and accretion onto a single BH problems in GR are now well developed, simulations of disk accretion onto BHBHs are still in their infancy [2–4, 13, 14]. Vacuum calculations offer an accurate description of the spacetime and the GWs emitted close to merger in typical cases. Determining the EM signatures requires a GRMHD computation in this dynamical BHBH spacetime.

Here we report the first fully GRMHD simulation of a magnetized, circumbinary BHBH accretion disk. The effective viscosity driving accretion arises from MHD turbulence triggered by the magnetorotational instability (MRI) [15]. This effective viscosity competes with the tidal torques exerted by the binary, so that a quasi-stationary state is reached prior to binary-disk decoupling [6, 7]. This state has been simulated both in Newtonian [6] and in Post-Newtonian [16] gravitation. Typi-

cally, the computational domain excludes the region near the BHs and artificial inner boundary conditions are imposed. Recent Newtonian studies [17] make clear the importance of imposing the correct boundary conditions on the flow inside the central disk hollow and near the BHs, further motivating a treatment in full, dynamical GR whereby BH horizons can be modeled reliably.

The basic evolution of the system is as follows: For large binary separations  $a$ , the inspiral time due to GW emission is much longer than the viscous time ( $t_{\text{GW}} \gtrsim t_{\text{vis}}$ ), so that the disk settles into a quasi-stationary state. For equal-mass BHs, the binary tidal torques carve out a partial hollow in the disk [5, 6, 8, 10] of radius  $\sim 2a$  and excite spiral density waves throughout the disk, that dissipate and heat the gas. However, gas can penetrate the hollow in response to the time-varying tidal torque [8, 10, 16, 18]. At sufficiently small separations  $t_{\text{GW}} \lesssim t_{\text{vis}}$ , and the BHBH *decouples* from the disk. The disk structure at decoupling crucially determines its subsequent evolution and the EM emission. GW emission close to merger leads to mass loss [19, 20] and may induce remnant BH recoil [21], which give rise to further characteristic EM signatures. Here we simulate the system in two different epochs: (I) The pre-decoupling phase ( $t_{\text{GW}} > t_{\text{vis}}$ ) and (II) the post-decoupling phase ( $t_{\text{GW}} < t_{\text{vis}}$ ), including the inspiral and merger of the BHBH. We consider equal-mass, nonspinning binaries. While the BH mass scales out, we are primarily interested in total (ADM) masses  $M \gtrsim 10^6 M_\odot$  and low density disks for which the tidally-induced binary inspiral and the disk self-gravity are negligible.

We use the Illinois numerical relativity code to carry out our simulations. The code has been extensively tested [22, 23] and used in our earlier BHBH simulations in gaseous media [2, 18]. For details and equations see [22–24]. The main new feature concerns our vector potential ( $\mathcal{A}_\mu = \Phi n_\mu + A_\mu$ ) formulation for the magnetic induction equation, where  $n^\mu$  is the future-directed timelike unit vector normal to a  $t = \text{const.}$  slice

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and  $n^\mu A_\mu = 0$ . We introduce a new generalized Lorenz gauge condition  $\nabla_\mu \mathcal{A}^\mu = \xi n_\mu \mathcal{A}^\mu$ , where  $\xi$  is a parameter (typically  $\xi = 4/M$ ) and  $M$  is the total BHBH (ADM) mass. This condition results in damped traveling EM gauge modes, preventing the spurious emergence of B-fields associated with refinement boundaries [25].

The disk initial data represent an equilibrium disk orbiting a single Schwarzschild BH [18, 26] with an inner disk edge at  $R_{\text{in}} = 18M = 1.8a$ , where the specific angular momentum  $\ell_{\text{in}} = 5.15M$  at  $R_{\text{in}}$ , and a nearly Keplerian rotation profile parameter  $q = 1.7$ . We adopt a  $\Gamma$ -law equation of state with  $\Gamma = 5/3$ , appropriate for a disk composed of an ideal, nonrelativistic gas. We seed the disk with a weak poloidal B-field as described in [24]. The maximum relative strength of the initial B-field in the equatorial plane is  $(P_M/P)_{\text{max}} = 0.025$ . Here  $P_M \equiv B^2/8\pi$  is magnetic pressure,  $P$  is gas pressure, and  $B^\mu$  is the magnetic field measured in the comoving frame of the fluid.

Prior to decoupling we can neglect the slow BHBH inspiral. We model the spacetime during this epoch by adopting the BHBH metric derived in the conformal thin-sandwich (CTS) formalism [27], whereby the spacetime is stationary in the corotating frame (see [18] for details). The inner part of the disk settles into a quasiequilibrium state on a “viscous” time scale

$$\frac{t_{\text{vis}}}{M} = \frac{2R_{\text{in}}^2}{3\nu M} \sim 6500 \left( \frac{R_{\text{in}}}{18M} \right)^{3/2} \left( \frac{\alpha}{0.13} \right)^{-1} \left( \frac{H/R}{0.3} \right)^{-2}, \quad (1)$$

where  $\nu$  is the effective viscosity induced by MHD turbulence [15]. This viscosity can be fit (approximately) to an ‘ $\alpha$ -disk’ law for purposes of analytic estimates. Here  $R$  is the disk radius,  $\nu(R) \equiv (2/3)\alpha(P/\rho_0)\Omega_K^{-1} \approx (2/3)\alpha(R/M)^{1/2}(H/R)^2 M$ ,  $H$  is the disk scale height, and we have assumed vertical hydrostatic equilibrium to derive an approximate relationship between  $P/\rho_0$  and  $H/R$  (see [28]). Equating the viscous time scale and the GW inspiral time scale yields the decoupling separation

$$\frac{a_d}{M} \approx 13 \left( \frac{\alpha}{0.13} \right)^{-2/5} \left( \frac{H/R}{0.3} \right)^{-4/5}, \quad (2)$$

where the normalizations give the typical parameters our simulations obtain for the relaxed state. Note, that for the geometrically thick, magnetic disks we treat, the expected decoupling radius is an order of magnitude smaller than typical thin-disk cases [6, 29]. We thus set our initial binary separation at  $a/M = 10$  (orbital period  $2\pi/\Omega = 225M$ ).

We evolve the system using the CTS spacetime for  $\sim 45$  binary orbits ( $10,000 M$ ) to allow the inner parts of the disk to settle into a quasistationary state. This epoch (1) models the pre-decoupling phase and (2) provides realistic, relaxed disk initial data for the post-decoupling inspiral phase. We model the post-decoupling phase by continuing the GRMHD evolution in the dynamical spacetime of the inspiraling and merging BHBH

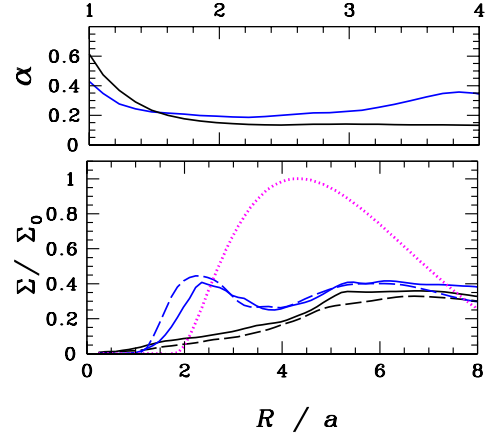


FIG. 1. The disk  $\alpha$  parameter (upper panel) and surface-density  $\Sigma$  (lower panel) profiles.  $\Sigma_0$  is the maximum surface density at  $t = 0$ . Dotted magenta line is the initial data, solid lines are at decoupling, and dashed lines are at merger. Black lines are from the “no-cooling” case, and blue lines are from the “cooling” case.

binary. We treat two extreme opposite limiting cases: “no-cooling”, which allows for gas heating via shocks induced by tidal torques and MHD turbulence, and “cooling”, which removes all the heat generated via an effective local emissivity  $\Lambda$  of the form  $T^{\mu\nu}{}_{;\nu} = -\Lambda u^\mu$  as in [30]. Our “cooling” case, though artificial, provides a representative example of the effects of cooling and has been adopted in previous work (e.g. [16, 31]). The particular “cooling” prescription we use drives the gas to isentropic behavior, i.e.  $P/\rho_0^\Gamma = \text{const}$ . The cooling timescale is set to the local, Keplerian orbital period. Our simulations resolve the BH horizons and we impose *no inner boundary conditions*. In the pre-decoupling phase our grid consists of a hierarchy of 6 refinement levels with (coarsest, finest) resolution of  $(5.33M, 0.16M)$  and outer boundary at  $250M$ . We resolve the fastest-growing MRI mode by at least 10 grid points in the bulk of the inner disk. We add two extra levels centered on each BH in the post-decoupling phase, increasing the (coarsest, finest) resolution to  $(4M, M/32)$ . After merger and ringdown we freeze the spacetime evolution, but continue to evolve the plasma. Equatorial symmetry is imposed throughout. We normalize results to those for a single BH that we evolved with the same initial magnetized disk and BH mass equal to  $M$ .

The initial disk (see Fig. 1) is not in equilibrium around the binary as it is perturbed by the binary torques. This leads to spiral density waves in the disk which dissipate and heat the gas. The gas gains angular momentum and the surface density profile moves slightly outward. Magnetic winding converts the poloidal field into one with a large toroidal component. MRI is induced, resulting in turbulent flow. After about 20 binary orbits ( $\sim 4 - 5$  disk orbits at the pressure maximum) the

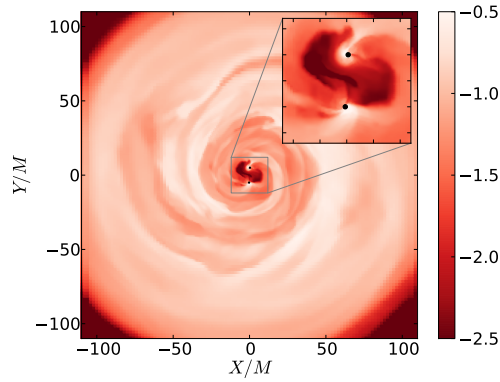


FIG. 2. Orbital plane snapshot of rest-mass density  $\log(\rho_0/\rho_{0,max})$  from the “no-cooling” simulation at  $t \sim 10000M$  in the relaxed disk, prior to decoupling. The inset zooms in on the region close to the BHs.

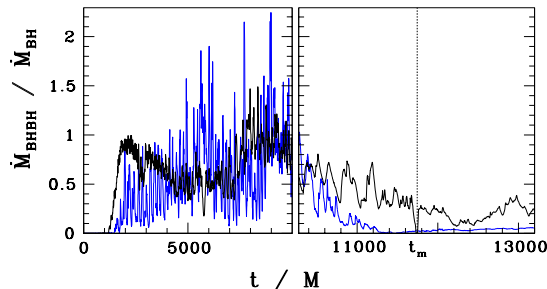


FIG. 3. Time-averaged binary accretion rate  $\dot{M}_{BHBH}$ , normalized to the average value for a single BH  $\dot{M}_{BH}$ , versus time. Colors have the same meaning as in Fig. 1. Left panel: pre-decoupling ( $a = \text{const}$ ) phase. Right panel: post-decoupling (inspiral) phase.  $\dot{M}_{BH} = 0.45n_{12}M_8^2M_\odot\text{yr}^{-1}$  where  $M_8 \equiv M/10^8M_\odot$  and  $n_{12} \equiv n/10^{12}\text{cm}^{-3}$  is the initial maximum gas particle number density.

MRI saturates, driving disk accretion onto the BHBH. In the relaxed disk prior to decoupling we measure a time-averaged Maxwell-stress as in [32] at  $20M < R < 30M$ , and find  $\alpha = 0.13$  for the “no-cooling” (see Fig. 1) and  $\alpha = 0.2$  for the “cooling” case. The magnetic-to-gas-pressure ratio  $1/\beta$  ranges from 0.1 to 5 in the bulk of the disk.

Cooling influences the global disk structure. In particular, we observe matter pile-up near the inner disk edge only with cooling (see Fig. 1), as has previously been found in [7, 10, 11, 16]. The binary maintains a partial hollow in the disk (see Fig. 1) by exerting torques on the plasma, while the MRI-induced effective viscosity drives matter inward. Cooling leads to smaller scale height and lower  $\nu$ , which explains the enhanced pile-up at  $R_{in}$ . We confirm the result in [10, 11, 16, 18] that non-negligible amounts of gas are present inside the cavity.

Accretion occurs predominantly via two spiral density

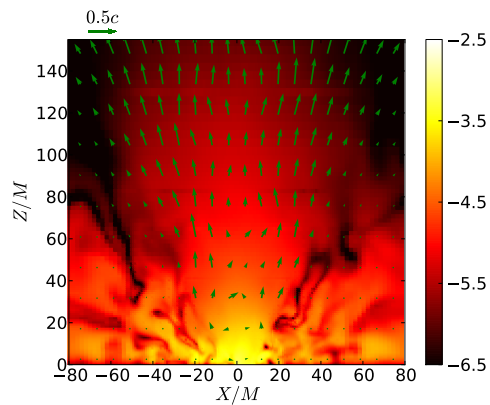


FIG. 4. Meridional snapshot of magnetic pressure  $\log(P_M/\rho_{0,max})$  and fluid velocity vectors at  $t \sim 10000M$  for the “no-cooling” case.

streams inside the cavity (see Fig. 2). We find that accretion exhibits an alternating pattern by accreting primarily on one of the BHs for about half a binary orbit. This is similar to flow features observed in [11]. The behavior has been attributed to a gradual increase of disk-eccentricity [10], which weakens one of the two streams when the BHs pass near the disk-apocenter and strengthens the other stream at pericenter.

Prior to decoupling, but after an initial transient phase ( $5000M \lesssim t \lesssim t_{\text{vis}}(R_{in})$ ), the accretion rate  $\dot{M}_{BHBH}$  settles to values comparable to those onto a single BH of mass  $M$  (see Fig. 3). We perform a Fourier analysis of  $\dot{M}_{BHBH}$  and find that the strongest contributions arise at  $f \sim 2/3\Omega$  in both of our cases. This is likely associated with the dominant (2,3) Lindblad resonance [10]. During the early inspiral the inward drift of the disk edge lags behind the binary orbital decay, decreasing  $\dot{M}_{BHBH}$ . In contrast to the magnetic-free case [18], the accretion streams *remain present* until merger at  $t_m$  for the “no-cooling” case and up until  $t - t_m \gtrsim -400M$  for the “cooling” case. At merger  $\dot{M}_{BHBH}$  decreases gradually to about 30% of the single, quasi-stationary BH accretion rate,  $\dot{M}_{BH}$  (see Fig. 3).

The remnant BH settles down via quasi-normal mode ringing to a Kerr-like BH with mass  $M_f \sim 0.95M$  and dimensionless spin  $s = J_f/M_f^2 = 0.68$ . In the “cooling” case the inner disk edge reaches  $R_{in}(t_m) \sim 10M$  at merger, while the edge is more dispersed in the “no-cooling” case (see Fig. 1).

Prior to decoupling we detect persistent, magnetized, mildly relativistic ( $v \gtrsim 0.5c$ ) collimated outflows in the polar regions (see Fig. 4) in both cases. After merger there is an increase of the velocities in the outflow reaching Lorentz factors  $W \lesssim 4$  for the “no-cooling” case, while the outflow in the “cooling” case remains relatively unchanged. These properties persist throughout the postmerger evolution. After merger the effective, tur-

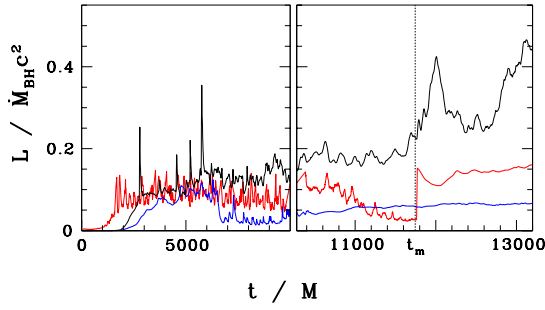


FIG. 5. The Poynting luminosity  $L_{EM}$  measured at  $R = 100M$  as a function of time (blue line for “cooling”, black line for “no-cooling”). The cooling luminosity  $L_{cool}$  from the “cooling” case (red line).  $\dot{M}_{BH}c^2 = 2.58 \cdot 10^{46} \text{ ergs}^{-1} n_{12} M_8^2$ .

bulent viscous torque will cause the gas to refill the cavity and accrete on the merger remnant. Thus, brightening crucially depends on the surface density at decoupling. If there is only a small pile-up and the majority of gas lies at radii  $R \gtrsim 40M$ , then a significant brightening will take  $t_{vis}(R \gtrsim 40M) > \mathcal{O}(10^4 M)$  following merger. Using Eq. (1) we estimate  $t_{vis}(R = 40M) \gtrsim 22000M$  ( $\alpha \sim 0.13, H/R \sim 0.3$ ) for the “no-cooling” case and  $t_{vis}(R = 14M) \gtrsim 6800M$  ( $\alpha \sim 0.27, H/R = 0.17$ ) for the “cooling” case, respectively. We observe the surface density profile diffusing inward, but we have not followed the evolution for this long. The Poynting luminosity ( $L_{EM} \equiv \int -T_t^{(EM)} \sqrt{-g} dS$ ) across a sphere at  $R = 100M$  and the (approximate) luminosity from disk cooling ( $L_{cool} \equiv \int \Lambda u_t \sqrt{-g} d^3x$ ) are shown as functions of time in Fig. 5. We find a sudden enhancement in the Poynting luminosity for the “no-cooling” case beginning at merger and growing for  $\lesssim 200M$ . This enhancement originates from shocked gas in the immediate vicinity of the binary and escapes mainly through the polar regions. It is absent for the “cooling” case, for which there is less gas near the binary prior to merger. Heat generated by shocks is also removed in the cooling case, leaving less energy available for conversion to a Poynting flux. In Fig. (5) we also plot the cooling luminosity for the “cooling” case, for which we also observe a sudden jump at merger. We find that the outward flux of kinetic energy is much smaller in both cases. Total efficiencies  $\epsilon \equiv L/\dot{M}_{BH}c^2$  increase to  $\epsilon = 0.25$  at merger.

The Poynting luminosity is presumably reprocessed at larger distance from the remnant. The characteristic frequencies of the total emitted EM radiation will depend on the BH masses, disk densities and dominant cooling mechanisms. We plan to investigate these issues, along with other precursor (e.g. twin jets) and afterglow effects, different mass ratios, and different BH spins more thoroughly in future work.

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